Energy Policy 120 (2018) 94–99

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Promises and limitations of nuclear fission energy in combating climate change[☆]

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A R T I C L E I N F O

Keywords:
Fission energy
Fusion energy
Climate change
Nuclear reactor licensing

A B S T R A C T

The most serious problem facing humanity is that we have only a few decades in which to implement effective measures to stop global warming. For these years up to about 2065, fission energy from light water thermal reactors is relevant as an available, developed and proven non-carbon technology with the potential to make an essential contribution to the mitigation of global warming, in addition to renewable energy. Nuclear power is expected to have more economic advantages than intermittent renewable sources for generating base load electrical energy requirements. This would be especially important in the years from about 2025 up to 2065, during which one cannot expect a serious contribution from nuclear fusion and even less from fossil fuels with carbon capture and storage (CCS) facilities. In a strategy to eliminate all non-CCS coal power stations, some 1600 MW of nuclear power would be required and sufficient to cover the base load for the electrical energy supply system. This nuclear expansion should be accompanied by effective international safety assurances, including a mandate to stop construction of unsafe nuclear power plants. In the long term, after 2065, we expect inherently safe molten salt thorium reactors to compete with fusion reactors.

1. Introduction – selection of nuclear technology

Humanity must face reality: the climate is changing and measures to mitigate climate change are imperative. Climate change is predominantly influenced by human activities emitting greenhouse gases (GHG) into the atmosphere (Medhaug et al., 2017; IPCC, 2014), so one mitigation measure is the reduction of these emissions (Meinshausen et al., 2009). As a considerable portion of GHG emissions comes from the production of electricity in the energy sector, a major transformation of the electrical energy supply system is needed. GHG emissions are inherent to the combustion process in fossil fuel power plants. Therefore, these power plants need to be replaced over the next few decades by non-GHG-emitting power plants, unless the fossil fuel power plants are supplied with carbon capture and storage (CCS) facilities. Nuclear technology is the only developed GHG emissions-free energy source capable of replacing fossil fuel energy sources in the given time scale, safely, economically, reliably and in a sustainable way. Consequently, nuclear energy must play a major role in this necessary transformation of the 21st century energy supply system (Brook et al., 2014). The scope of this paper is to analyse which type of nuclear technology could make a substantial contribution to combating climate change.

When selecting the most appropriate nuclear technology to combat global warming, we must consider both nuclear fission and nuclear fusion. Of these two basic forms, we have over fifty years experience with nuclear fission for energy production. Over 400 fission power stations have been in operation for more than half a century and we have decades of experience in their construction and operating problems. Besides experience with nuclear fission reactors in the civil sector, substantial experience has also been accumulated in the military sector. Fusion energy, on the contrary, still faces basic, physical problems as well as many practical ones. In spite of decades of research, it has yet to reach the stage where it can produce a viable, positive energy balance from the fusion device. With fission energy, positive energy balance was achieved in 1942, but heroic efforts to attain the goal of energy gain in fusion have had to focus on plasma physics rather than on the economic and practical problems of constructing and operating fusion reactors.

The initial goal of achieving positive energy balance is pursued in ITER (International Thermonuclear Reactor), the largest current magnetic fusion device under construction. ITER is based on the Tokamak fusion concept, as a follow-up device from the Princeton Tokamak TFTR (Tokamak Fusion Test Reactor) which achieved 10.7 MW of fusion power in 1994 (PPPL, 2017). Assuming ITER successfully achieves positive energy balance, the aim will then be to develop the next fusion

[☆] This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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https://doi.org/10.1016/j.enpol.2018.05.027
Received 22 November 2017; Received in revised form 29 April 2018; Accepted 10 May 2018
Available online 26 May 2018

device, DEMO, into a working fusion power station with all its components of power conversion and tritium production. Whilst achieving positive energy balance in ITER is probably only a question of time, a big question mark hangs over the second goal: the ITER device is based on the Tokamak principle and the essential step in achieving a positive balance in the fusion chamber is to reduce losses of deuterium and tritium from plasma. This could be attained, failing a better solution, by increasing plasma volume with a corresponding increase of the toroidal plasma chamber. Mainstream development, at least with ITER, seems to be heading in that direction. With a big enough plasma chamber, Tokamak fusion will most likely be achieved, but with an installation of elephantine size and complexity. Consequently, Tokamak power plants are unlikely to be built outside a small number of leading, technologically advanced countries. One cannot, therefore, expect Tokamak plants to be built early enough and in sufficient numbers to have a bearing on climate change.

Outstanding problems of a more technical nature with Tokamak fusion are the production of tritium, magnets under strong neutron flux, first wall radioactivity and its replacement. Most of these problems would be associated with any kind of magnetic fusion geometry. New concepts, different from the Tokamak one, are emerging, some of which were described recently (Gibbs, 2016) in the "Scientific American". Regardless of whether these new concepts may have a better chance of achieving fusion, it will be too late for them to have a timely effect on climate change. It is a long and winding road to energy production in large commercial power stations of any type of fusion technology. Laser fusion at the US Lawrence Livermore Laboratory achieved a break-even in pellet burning in 2014 (Betti, 2016). However, that would cover only about 1% of the energy consumed in the whole laser fusion installation. Lengthy and uncertain development would be needed to reach the remote goal of an overall positive balance in laser fusion. That leaves fission technology as the only effective nuclear source for climate mitigation in the time window available to us between now and 2065.

2. A comment on carbon capture and storage (CCS)

Most people lack a correct appreciation of the quantities involved in CCS. Coal production is a massive industry worldwide. Thousands of trains and ships transfer coal from mines to power stations. The amount is staggering: annual consumption is close to ten billion tons. The mass of emitted CO_2 obtained by coal combustion amounts to up to three times the mass of coal used, so storing some twenty billion tons of CO_2 every year defies imagination. Experimental installations have not achieved economic viability. Some are quite large, sequestering several million tons of CO_2 annually, but with inefficient CO_2 removal. There is no chance of increasing the scale a thousand-fold, no idea of where to store tens of billions of tons of CO_2 per year, or, on that scale of storage, how to prevent it from escaping. As one author, independent of the coal industry, surveying the CCS efforts puts it (Biello, 2016), one gets the impression that basically the idea of CCS for climate mitigation is just an alibi for the coal industry to continue burning coal regardless of the effect it has on the climate. An additional argument to our statements regarding CCS is the failure to demonstrate a clean coal technology in the Kemper County plant (Wagman, 2017).

3. Understanding the urgency of the climate situation

The time left to humanity before uncontrollable physical and consequently social changes take place is estimated at only a few decades. A report by the IPCC (International Panel on Climate Change) AR 5 WG 3 (IPCC, 2014) states that between 2000 and 2010 GHG emissions grew at 2.2% a year, almost twice as fast as in the previous 30 years. At that rate, the report states, the world will pass the 2 °C temperature rise by 2030. The last GHG emission figure for the period 2000–2010 is (49 ± 4.5) Gt CO2 eq/year. The connection between carbon concentration in the atmosphere and global temperature rise has been disputed in recent years. The so-called "global warming hiatus" between the years 1998 and 2012 appears to show a slower global temperature growth than would be expected from climate models and the rise of carbon concentration. This has been used by some climate change sceptics to deny that the rise of carbon concentration in the atmosphere is the cause of global warming. However, ocean scientists claim that the hiatus can be explained by the "Decadal Pacific Oscillation" phenomenon. The years 2015, 2016, and part of 2017, the hottest years recorded, show the end of the oscillation period, with a return to faster temperature rise leading to general agreement about long-term trends. The chief scientist at the British Meteorological Office, Stephen Belcher, thinks that with warming after 2015 global temperature rise will follow the long-term trend. A detailed account is given in Nature (Medhaug et al., 2017). In the light of new data on the climate during the years 1998–2012, authors Medhaug et al. think they understand the cause of the hiatus and "are more confident than ever that human influence is dominant in long-term global warming".

Important quantification, based on long-term trends, of the limits to future carbon emission is provided in the paper by Meinshausen et al. (2009). To compare the data, we note that, in the period 1970–2010, the share of fossil fuel combustion in the total GHG emissions was 78%. We quote the following extremely important results: "Limiting cumulative CO_2 emissions over 2000–2050 to 1000 Gt yields a 25% probability of warming exceeding 2 °C and the limit of 1440 Gt yields a 50% probability - given a representative estimate of the distribution of climate system properties." As the emission of CO_2 during the interval 2000–2006 amounted to 234 Gt of CO_2, the magnitude of the problem is apparent. Assuming a continuation of average annual emissions amounting to 36.3 Gt from fossil fuels, forestry and land use, we will exhaust our emission budget by 2027 or 2039 (for respectively 25% or 50% probability exceeding 2 °C). The current global temperature increase is close to 1 °C, yet we are already witnessing an abundance of unpleasant climate changes. The latest instances are the floods in Texas, Florida, and the Caribbean islands. Informed people and scientists dread a future when the world will be confronted with damaging climate changes: floods, droughts, hurricanes, unbearable temperatures, with multitudes of millions migrating in search of a better place to live. That future is only a few precious decades away. A return to pre-global warming conditions is probably already impossible. The alarming new United Nations (UN) Environmental Report 2017 (UNEP, 2017) shows a wide discrepancy between annual carbon emissions predicted for 2030 and the emissions consistent with the long-term 2 °C global temperature increase. The gap (excess of predicted emissions) is estimated at 11.0–13.5 Gt CO_2.

4. Arguments for nuclear technology

Given that the time left for effective action to mitigate future trends is at most two or three decades, what measures can be taken? Renewable energy should be developed as fast as possible. Many people hope that the practically unlimited capacity of solar energy will be the saving grace. However, solar energy is not developing fast enough, as its proponents warn (Koningstein and Fork, 2014). Although solar energy might provide a practically unlimited resource, the effective rate of construction of solar devices is technically limited by the energy consumed in their production, as several studies have shown (Murphy and Hall, 2010). Additionally, solar energy is dependent on a daily cycle and requires expensive energy storage. Nuclear fission energy, providing a base energy load at all times, should be cost effective when compared with intermittent sources requiring additional energy storage. Consequently, nuclear fission, with its potential for a large-scale build-up not later than 2025, cannot be left out of the equation. Unlike nuclear fusion, improved nuclear fission is ready for expansion. Technical advances and cost reductions are possible with unification of design and by developing licensing procedures within a large-scale nuclear programme proposed for combating climate change.

5. Selection of nuclear fission technology

Which nuclear technology to select is obvious, if the acceptable choice assumes long operating experience with a number of reactors built of basically the same design. Light water-cooled reactors fuelled with 3–4% enriched uranium have been in operation since the 1980's, many having reached a full, 40 year operational life.

During these decades of experience, a number of safety advances have been made. Most notably, after the core melting accident at Three Mile Island in 1979, extensive retrofits were implemented on pressurised water reactors (PWR), leading to considerable operational and safety improvements. In this early accident, very little radiation escaped into the surroundings but the damage to the reactor core was irreparable, costing the utility billions of dollars. Such damage is clearly unacceptable and the investment in additional safety devices and operational practices was proportionately high.

That accident contributed enormously to the safety of PWR reactors built later or retrofitted with safety systems. The situation was very different with the Soviet reactor of another type, the RBMK (a high power reactor with pressure tubes) at Chernobyl, which suffered extensive core damage in 1986. This reactor, unlike the one in the Three Mile Island accident, had no containment building to stop the spread of radiation into the surrounding area. Consequently, a large amount of radioactivity from the reactor core was released into the environment, reaching many neighbouring countries and leaving huge areas around the reactor uninhabitable.

A recent, serious accident took place in Japan in 2011 in a boiling water reactor (BWR) as a consequence of a catastrophic earthquake and associated tsunami. In this case, the nuclear safety systems to shut down the reactors operated correctly, but core damage developed over the following days owing to damage to the secondary cooling system (Ng, 2011). The nuclear part of the plant behaved correctly but the essential secondary cooling systems were flooded owing to an incorrect estimate of the predicted height of a tsunami.

Clearly, there are specific safety problems intrinsic to nuclear fission energy, on account of its very high radiation content. Safety of nuclear systems and their components has been of prime importance from the outset, but sometimes unexpected problems are only discovered after years of operation. One such problem was the discovery of serious corrosion in certain important reactor components, which resulted in the establishment of regulatory requirements for replacement of the respective parts.

Exchange of information on any safety problems through the WANO (World Association of Nuclear Operators) is therefore of the utmost importance, and the three accidents cited above are strong arguments for the institution of international licensing procedures, at least for future nuclear plant constructions.

The need to decarbonise energy sources introduces new criteria into economic selection of energy sources. With increasing carbon tax after 2025, coal power will become uncompetitive, whilst it becomes clear that CCS-equipped coal power has no chance of being economical. Gas is somewhat better, but nevertheless with no long-term future. Very large carbon-free energy reserves of hot dry rock have been shown to be of limited exploitability (Knapp and Coffou, 1977). That leaves us with nuclear, hydro, solar and wind energy as the carbon-free sources with a large enough potential to mitigate global warming. However, the economy will still decide from among a variety of carbon-free sources, so nuclear energy will have to face economic competition from these various sources. Both solar and wind energy costs are likely to decrease, but so will the cost of nuclear fission energy in the years after 2025, assuming a build-up of about 1600 GW is needed to replace coal power stations (Knapp et al., 2017) and allowing for unification of designs and specialisation in the production of nuclear equipment. In the foreseeable future, during the period 2025–2065, we expect to see pronounced effects from standardisation of design in a large-scale nuclear programme putting the primary importance on carbon emission reduction rather than on the introduction of innovative reactor types. That is the reason we would not recommend a major introduction of Generation IV nuclear technologies in the years before about 2050 (Grape et al., 2014), despite growing support for nuclear energy.

Nuclear reactor costs were analysed by Michel Berthélemy and Lina Escobar Rangel (Berthelemy and Escobar Rangel, 2015). They argue, based on evidence from France and the USA, that construction costs of nuclear reactors can benefit from standardisation of design. They find that, contrary to other energy technologies, innovation leads to construction cost increases.

Power costs were also analysed by Geoffrey Haratyk (Haratyk, 2017). He presents the economic performances of existing American plants. While it is certainly an important paper, we think it is not a relevant comparison with the plants that would go into operation after 2025. A carbon tax was not included in the cost of coal energy, as it was considered irrelevant to the operation of American nuclear plants, most of which are more than thirty years old. However, in the future, the situation will be different. The nuclear programme proposed to replace all coal power plants assumes a nuclear build-up that could start by 2025 or later, when it is predicted that a carbon tax would grow from about \$50/tCO_2 in 2025 to about \$150/tCO_2 in 2105, when all the plants from the nuclear build-up starting in 2025 would be closed (OECD, 2013; Luckow et al., 2015). The advantage of nuclear energy over renewable energy is its permanent availability versus an intermittent mode of operation. Nuclear energy can be more economical as part of a mixed system, backing up intermittent renewable sources by covering the base load consumption - about one third of total consumption - the reason being that energy storage on a large scale is as yet an open problem with no economically viable solution in sight.

6. Supply limits of uranium for light water reactors

Following on from our selection of PWRs as the dominant light water technology, we need to discuss whether there is a sufficient fuel supply to keep them running, although the situation would be similar with any other light water technology, i.e. BWR reactors.

Attention was given to this question, as it is often stated that long-term fission energy faces a problem of limited supply of uranium. Our earlier study was aimed at establishing what would be the maximum contribution from estimated uranium resources to electricity production by PWR reactors without fuel reprocessing. The relevant period for combating global warming was assumed. Results were encouraging. Estimated future uranium resources of 17.3 million tons (OECD/NEA-IAEA, 2008) would allow construction of 3300 GW (Knapp et al., 2010). This result was positive enough to warrant proposing effective carbon emission reduction by replacing all non CCS-equipped coal power plants with nuclear PWR plants (Knapp et al., 2017). The requirement for new nuclear power plants amounts to 1600 GW, which is well below the estimated maximum potential for PWR plants under the conditions described.

Taking into account geological considerations when looking at the general upper limit, resources may be considerably greater (Pevec et al., 2012): up to 50 Mt. Clearly, availability of uranium fuel is more than adequate and is no drawback to a proposal to replace all coal plants with nuclear PWR plants.

As for the long-term future of nuclear fission energy beyond 2065, fuel resources can be covered through the use of U238 or Th232. Both these nuclides theoretically offer unlimited amounts of energy that would satisfy demand for many centuries, but they cannot operate without fissionable nuclides such as Pu239 or Th233. The most efficient way to obtain Pu239 is to separate it from the used fuel in PWR reactors. Plutonium 239 (with an admixture of other Pu isotopes) produced in PWR reactors can then be used to start fast breeder reactors with U238 or alternatively with a thorium 232 core and plutonium as a fissile fuel, until plutonium can be replaced with Th233, as is demonstrated more quantitatively in the paper by Knapp et al. (2016).

Table 1
Progress of PWR annual core melting probabilities.

Period of evaluation	Reactor generation	Annual core-melting probability
1969–1974	Generation II	10^{-4} to 10^{-3}
Mid eighties	Generation II after TMI accident	10^{-4}
1996	Advanced generation II (Sizewell B)	$2{\cdot}10^{-6}$
2010	Generation III + (AP 1000)	$5{\cdot}10^{-7}$

7. Safety status of PWR (pressurised water) reactors

The nuclear safety status of PWR reactors can be followed from the early extensive safety study WASH 1400 with its final report by 1974 (WASH-1400, 1975). It was an advanced probabilistic study, initially developed for the Apollo space project. The study starts by listing all the initiating events, each specified with the estimated occurrence probabilities that may lead, through sequences of subsequent events and also probabilistically estimated events, to reactor core meltdown, in the worst case scenario. Resulting core-melting probability is the sum of all probability chains leading from all initiating events to core melting. This basic method of nuclear safety evaluation uses the probabilities of the events in the sequence leading to core melting, so the process of safety evaluation necessarily evolves alongside the accumulation of experience with reactor components and systems. It also develops through the inclusion of hitherto overlooked initiating events. Early results have revealed inadequate overall security and have also pinpointed components that contributed to the problem, thereby indicating the measures needed to increase safety.

The progress made can be illustrated by the figures for the annual core-melting probabilities of PWR reactors over a span of 40 years (Table 1). Annual core-melting probabilities (ACMP) for Generation II PWRs were estimated in the early seventies and were in the range of 10^{-4} to 10^{-3} (WASH-1400, 1975; Minarick and Kukielka, 1984). The safety of Generation II PWR reactors improved in the mid-eighties thanks to measures implemented after the accident to the Three Mile Island (TMI) reactor (ACMP estimated as 10^{-4}, Phung, 1985). The ACMP for advanced Generation II PWR (Sizewell B PWR plant in the UK) in the mid-nineties was further improved and was assessed as $2{\cdot}10^{-6}$ (Meyer and Stokke, 1997). The ACMP for Generation III+ PWR (Westinghouse AP1000) was estimated as $5{\cdot}10^{-7}$ (Marques, 2011).

Core melting need not have external effects, as PWR reactors have a containment building covering the pressure vessel in order to prevent radiation spreading into the surroundings in the event of core meltdown. Modern containments have a typical failure probability of one in a thousand cases of core meltdown. Thus, the total annual probability of radiation escaping into the surroundings would be about 10^{-9} or even lower. For one thousand reactors, the probability of radiation escaping into the surroundings would still be extremely small compared with other industrial or natural risks: about one radiation release in a million years. However, this analysis assumes respect for all the external risk safety assessments, as examined in Bernard Cohen's great book: “Before it's too late” (Cohen, 1983). Unfortunately, the external risk was underestimated in the case of the Fukushima accident.

8. The need for international licensing of nuclear reactors

We anticipate strong initial opposition to a proposal for international licensing from many political and industrial interests. For international licensing, probably the best choice would be IAEA, an organisation with expertise and authority, which should be given an extended mandate to prevent constructions judged insecure and dangerous to neighbouring countries. Arguments against interference, in what could be argued as the sovereign right to develop and build technology freely within one's own country, should be confronted with a higher principle of respect for the rights and safety of the wider community of countries. Should the development of new technology risk having negative effects on other countries, the general principles of the UN should be invoked to stop it.

Radiation is an indiscriminate threat to life, unacceptable in war let alone in peace time. Many of us lived in the Cold War years, when thousands of nuclear war heads were on short notice alerts with the capacity to destroy humanity many times over. Only a few people had the imagination to see how close we were to total destruction of our world. Human mistakes, misreading, loss of control over nuclear weapon subunits such as nuclear submarines could have lit the fuse. We were lucky to survive. Nobody cared much, during those ludicrous times, about the additional danger of nuclear reactors. Admittedly, nuclear accidents in a single nuclear power station would not mean the end of civilisation, but they could nevertheless do lasting, cross-border damage. The introduction of international mandates for nuclear safety standards would undoubtedly be in the interest of all countries, including those which would be requested to apply additional safety measures in order to comply with international safety standards. For acceptance of universal nuclear safety rules, all present and future nuclear countries should accept controls by the IAEA with its mandate extended accordingly.

Even with our current licensing procedures, in the opinion of many nuclear experts a construction permit would never have been obtained for the Chernobyl nuclear plant. But that was back in Cold War times, when such “interference into national sovereignty” was unthinkable. However, the much more recent case of the Fukushima accident took place in a developed nuclear country expected to obey the highest safety standards. In the final analysis, that accident can be ascribed to the fact that investors disregarded the prediction made by Japanese seismic scientists as to the possible height of a tsunami. Presumably, the natural tendency of any enterprise to reduce investment costs resulted in the utility opting for a cheaper construction, in this case with disastrous consequences. We do not know whether this is the only case in which the utility compromised or gambled with safety, counting on probabilistic luck. Be that as it may, we should, wherever possible, reduce and eliminate cross-border risks to other countries. The construction of an estimated 1600 nuclear power plants, even with the purpose of combating as urgent a problem as global warming, cannot, therefore, be recommended without the establishment of an efficient system of international licensing. This principle of mandatory international licensing will be increasingly important should a programme of nuclear plant constructions be applied as a measure to stop global warming. The need for international licensing is also argued and strongly supported by other researchers (Budnitz, 2016; Raetzke and Micklinghoff, 2012).

9. Long-term promises of nuclear fission energy

It is perhaps too early to talk about long term promises of fission energy before prospects of nuclear fusion are better known. But unlike constantly updated mobile phones, in energy generation things do not change so fast. Construction-time for large, energy-production installations with a working life of 20–80 years is between 2 and 10 years and construction costs range from 1 billion to 10 billion US dollars (WNA, 2018). Looking beyond the immediate problems of climate change, Tokamak fusion could perhaps be developed by the 2050's but their large and complex installations, based on present concepts, would have little chance of commercial success and therefore a correspondingly small impact on the climate. New approaches to fusion may appear, but by the time they have passed through all the phases of technical development and commercialisation, it may well be close to the next century. Fast breeders, selected in Generation IV and Small Modular Reactor projects, could be contenders for long-term production of fission energy. Meanwhile, in 2011 the Chinese Academy of Science and

Government selected inherently safe thorium reactors, initially developed in the USA, for their strategic programme. Molten salt thorium reactors (MSTR) were reviewed in Serp et al. (2014). MSTR reactors promise to be inherently safe, core-melting-free, simpler and very likely cheaper, presenting a great challenge to any future fusion reactor. The outcome of the race between fission and fusion has by no means been determined. There may well be a long-term promise for fission energy. Thorium liquid-fuelled reactors could usher in a phase of safe and economical nuclear energy that would at least cover basic load consumption, combined with energy production from renewable sources. One strategy for the introduction of thorium reactors, after the line of PWR reactors, is described in Knapp et al. (2016).

The precondition for this era of abundant and inexpensive nuclear fission energy is an efficient, international system for controlling traffic of fissile materials, based on the principles of the Non-Proliferation Treaty (NPT) and an extension of the IAEA's mandate. The world has some 50 years to agree on it. The alternative - disrespect for and continued breaking of the NPT – is a likely path to nuclear disaster. The rational choice appears to be obvious, but we should not count on it without great progress being made in international politics and proliferation control. Hopefully, global climate threats might bring us all to our senses.

10. Conclusions and policy implications

A. Scientific information about global warming (IPCC, 2014) demonstrates that urgent measures are needed to prevent unavoidable, catastrophic world-wide disasters from occurring before the end of this century. The latest data from the U.S. National Aeronautics and Space Administration predict an accelerated sea-level rise reaching 65 cm by 2100 (Nerem et al., 2018), detailing an alarming future. A paper in Nature (Meinshausen et al., 2009) gives the allowed cumulative emission limits for carbon dioxide as 1000 Gt, in the years 2000–2050, with 25% probability of the global temperature rise exceeding 2 degrees. We are rapidly spending this credit in fossil-fuel carbon dioxide emissions at an annual level of about 36 Gt.

B. As nuclear fusion is unlikely to be developed in time and CCS even less so, Generation III light water nuclear fission reactors, being carbon-free, technically developed and with decades of experience, could be ready for large-scale deployment in the years 2025–2065. Light water reactors could make an important contribution to mitigating global warming over the next 50 critical years, long before nuclear fusion could make an essential contribution. We expect light water reactors to provide an economical base load in an energy production mix with intermittent, renewable energy sources.

C. Confirming dangerous climate trends, the UN Environmental Report 2017 predicts carbon emissions for 2030 hugely in excess (11–13.5 Gt of CO_2) of emissions consistent with the long-term 2 °C global temperature increase. Proposed linear replacement of all non-CCS coal power plants in the years 2025–2065 by nuclear plants would reduce annual CO_2 emissions in 2065 by 11.8 Gt (Knapp et al., 2017).

D. This large coal power plant replacement proposal, requiring 1600 GW of nuclear power, should be accompanied by corresponding international safety measures, probably by extension of the IAEA mandate, to stop cross-border risks in the event of nuclear accidents. We find increasing understanding and support for such developments in China (Geng et al., 2018) and the USA (Budnitz, 2016).

E. Of course, such large nuclear programmes cannot be realised without public support. Leading environmentalists such as J. Lovelock – once an opponent of nuclear energy (Talk at Adam Smith Institute, March 15, 2004) – and the eminent climatologist J. Hansen understand that action against global warming is urgent and that we cannot wait for the development of fusion energy. Awareness of the threat is growing. Let us hope that when the effects of global warming become evident to the majority it will not be too late for action.

F. Under the circumstances, owing to the uncertain technical and economic future of nuclear fusion, it would be irresponsible not to use the potential of proven fission energy to cover the base load of an electrical grid. For the next stage, after the 2060's, we can foresee the introduction of thorium reactors or fast breeders and, hopefully, the first fusion reactors, although the latter would face stiff competition from safe, simple, and consequently cheap, liquid fuel thorium reactors.

Acknowledgements

The authors are grateful to Miss Susan Kershaw, BA (Hons), Cert Ed, Licence es Lettres for improving the language quality and clarity of this manuscript.

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